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TECHNICAL NOTE

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PROJECT ECHO— SATELLITE-TRACKING RADAR

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by
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SUMMARY

The radar employed at the Bell Telephone Laboratories' Holmdel, New Jersey site for tracking the Echo I satellite was originally designed for the sole purpose of antenna pointing. Recently, however, it has also been employed to measure earth-balloon-earth path loss at regular intervals of time in order to ascertain the balloon's condition. The performance of the system and some of the data obtained are discussed.

PREFACE

The Project Echo communications experiment was a joint operation by the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and the Bell Telephone Laboratories (BTL). The equipment described herein, although designed by BTL as part of its own research and development program, was operated in connection with Project Echo under contract NASW-110 for NASA. Overall technical management of Project Echo was the responsibility of NASA's Goddard Space Flight Center.

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INTRODUCTION

The operational plan of the Project Echo communications experiment provided for pointing of the transmitting and receiving antennas from calculated orbital data. The angle-tracking radar was intended as a backup to this system. The radar was found to provide appreciably better pointing accuracy than the computed data. As a result, the orbital data are employed only to keep the antennas pointed approximately on target, with the radar - or optical telescope during periods of visibility - providing for more exact alignment.

According to the original concept the radar was intended only to serve the purpose of keeping the antennas positioned during communications experiments. In recent months these experiments have practically ceased, and the radar remains the only regular source of signal for studying transmission effects. Under the present plan of operation the balloon is tracked approximately once per week and its cross section determined from the strength of the reflected radar signal.

ANTENNA-POSITIONING PLAN

The antenna-positioning plan for the complete Holmdel, New Jersey terminal (Reference 1) is shown on Figure 1. Orbital information, taken off the paper tape by the tape reader, is converted from digital to analog form by the digital-to-analog converter.

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*The substance of this paper was published in the Bell System Technical Journal Vol. XL, No. 4, July 1961. It is republished here, with minor revisions, by permission of Bell Telephone Laboratories.

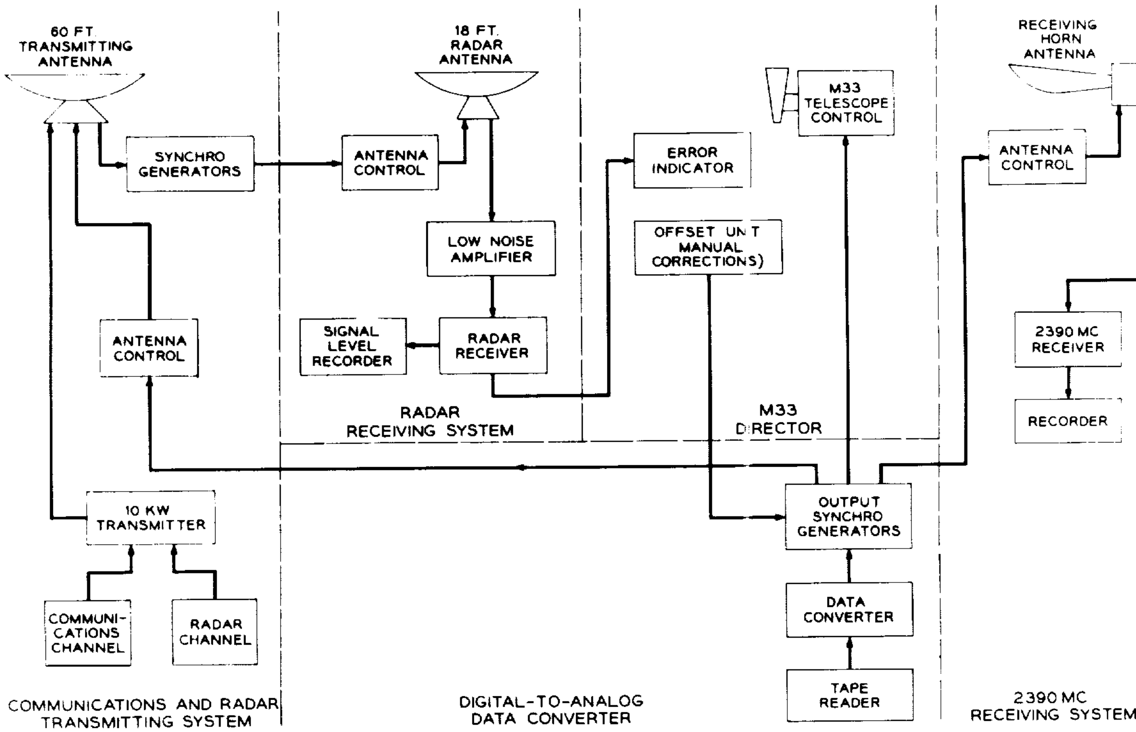

Figure 1 – Antenna positioning plan

This unit's synchro generators control the positions of the transmitting dish and receiving horn, as well as the optical telescope in the M33 gun director. The readout synchros on the transmitting antenna control the position of the radar receiving antenna. The pointing-error information derived from the radar is displayed before an operator at the M33 director; the operator applies corrections by means of a device which provides controlled amounts of offset in azimuth and elevation until the indicated errors are reduced to zero. During periods of visibility the optical telescope can also be employed to determine pointing information. It is evident that, once a signal is acquired, pointing could be done entirely with information from the radar or optical system. However, the control provided by the digital-to-analog converter makes acquisition much easier and provides an excellent tracking aid, with the radar or optical system simply indicating the corrections which are needed.

Up to the time of this writing there have been no attempts at auto-tracking the satellite. However, some limited experiments on automatic following of the natural moon are described herein.

DESIGN OBJECTIVES AND RADAR PERFORMANCE

The radar was designed to meet the following requirements:

(1) A capability of tracking the 100-foot balloon to a range of 3000 miles;

(2) A pointing accuracy of about ± 0.1 degrees;

(3) No accurate range information required; and

(4) Compatibility with the communications system, although sharing a common transmitter and transmitting antenna.

Except for some initial operating difficulties, the performance of the radar has been satisfactory. More than 100 successful tracking runs had been made by April 1961. It has almost always been possible to obtain a signal from the balloon as soon as it has risen a few degrees above the horizon and to maintain contact until it dropped to within a few degrees of the opposite horizon.

The low-noise parametric amplifier has been very stable with respect to both noise figure and gain. Over a period of months the sensitivity of the receiver remained at -150 dbm in a 100-cycle band; i.e., the minimum detectable signal is near this level. This is consistent with the receiver noise power output calculated in Appendix A.

During periods of visibility it has been possible to compare the radar pointing information with the more accurate information obtained by optical means. This comparison is accomplished by alternating between the offset required to obtain zero indicated optical error and that required to obtain zero indicated radar error. The radar and optical data usually agree to within one to two tenths of a degree, except for short periods on some adverse passes. One set of data obtained in this manner is plotted in Figure 2, the optical data being used as a standard of comparison. Between 0950 and 0951 GMT the balloon was passing through its point of nearest approach. As is usually the case, the error in the computed orbital azimuth data reached a maximum at this time, nearly 1.2 degrees. It is evident that the radar data are considerably better than the computed data, especially in azimuth.

The radar system is subject to errors due to parallax between the transmitting and the receiving antennas, to antenna lag at the higher rotation rates, and to lack of exact alignment between the various axes in the receiving antenna. Although each of these errors is small, they can add up to significant amounts for parts of some adverse passes. Fortunately, the enhanced error does not last long and is maximum at the balloon's point of nearest approach, where the signal level is great enough to allow for some discrepancy in pointing. The radar data, however, have been found more accurate than the orbital data even on these adverse passes.

The received signal (Figure 3) as indicated by the AGC voltage, for part of pass 2407, was recorded on February 24, 1961. The smooth curve is a plot of the theoretical value of the signal strength. Over the period of time shown, the actual signal does not differ appreciably from the calculated value except during periods of deep fades. The fades shown on this chart are typical, except for the unusually deep one at the right-hand side. Scintillations are usually considerably greater at the beginning and at the end of a pass

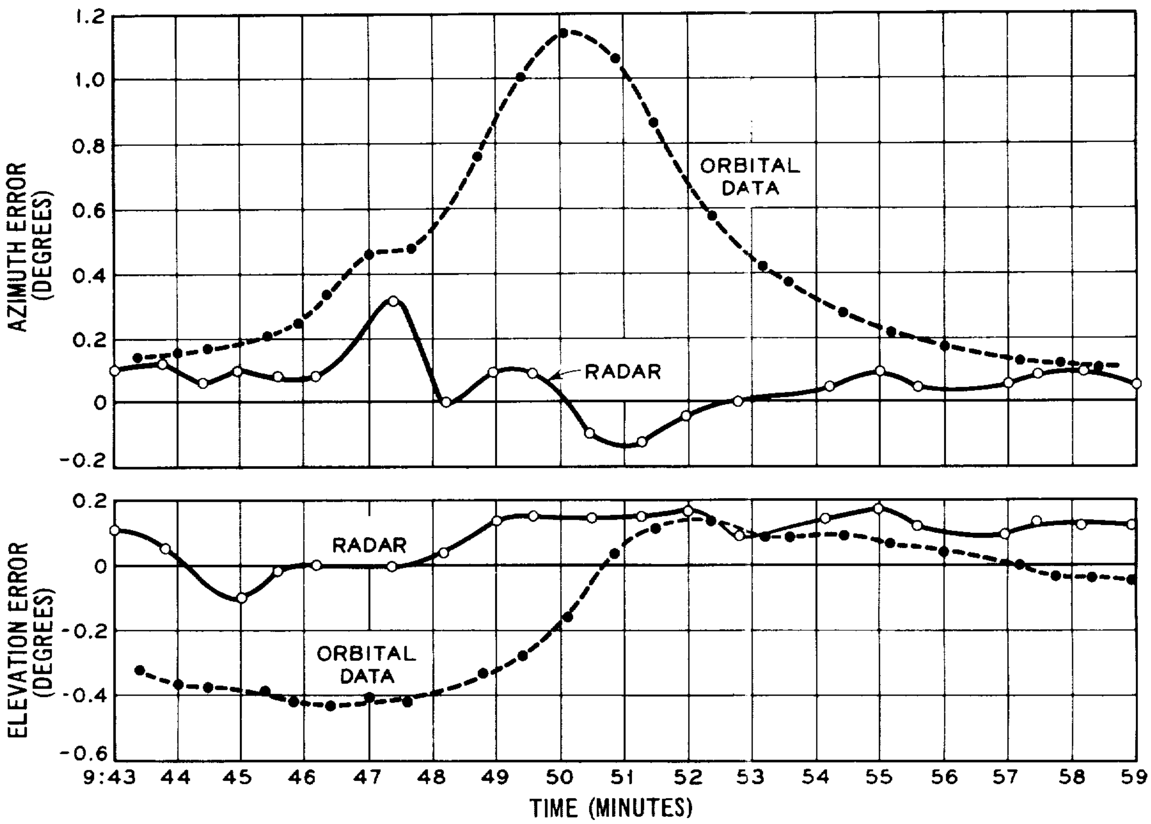

Figure 2 – Radar vs. optical pointing

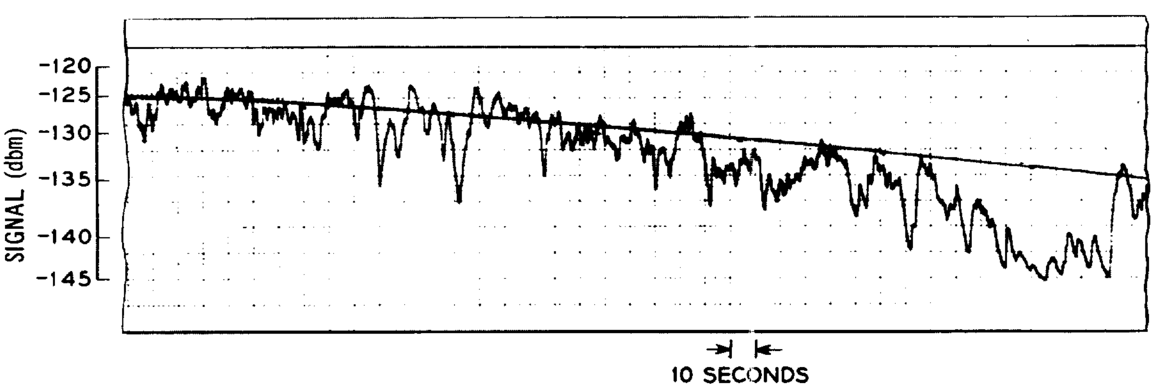

Figure 3 – Return signal from the satellite, pass 2407 (February 24, 1961)

than at the midpoint, probably due to the atmospheric effects when the balloon is near the horizon.

Charts similar to the one shown in Figure 3 have been prepared for 40 passes of the satellite. From these charts the average difference between the actual signal level and the theoretical value has been obtained for 33 passes between October 20, 1960 and March 2, 1961 (Figure 4). A smooth curve was drawn through an average of these points in an attempt to determine any long-time trend. The curve indicates some falling off in average signal strength since the recording started, but not more than about 1.5 db, which is less than the spread from one pass to the next, and may be insignificant. No significant change in scintillations was noted for the period recorded. It is evident that no great change in the size or shape of the balloon had accurred by April 1961; unfortunately, equipment was not set up to record accurate data before October 20, 1960.

On numerous occasions this radar has been used to track the moon; a recording of the received signal for part of one such operation is shown in Figure 5. An outstanding feature of the record is the rapid and continuous fading of the signal. These fluctuations are known to be greater and more rapid than is apparent on this chart, where the indications are limited by the time constant of the recording equipment. From the average signal level the calculated earth-moon-earth path loss was 268.7 db, compared to the 268.1 db quoted by Trexler (Reference 2) for this frequency (see Appendix B).

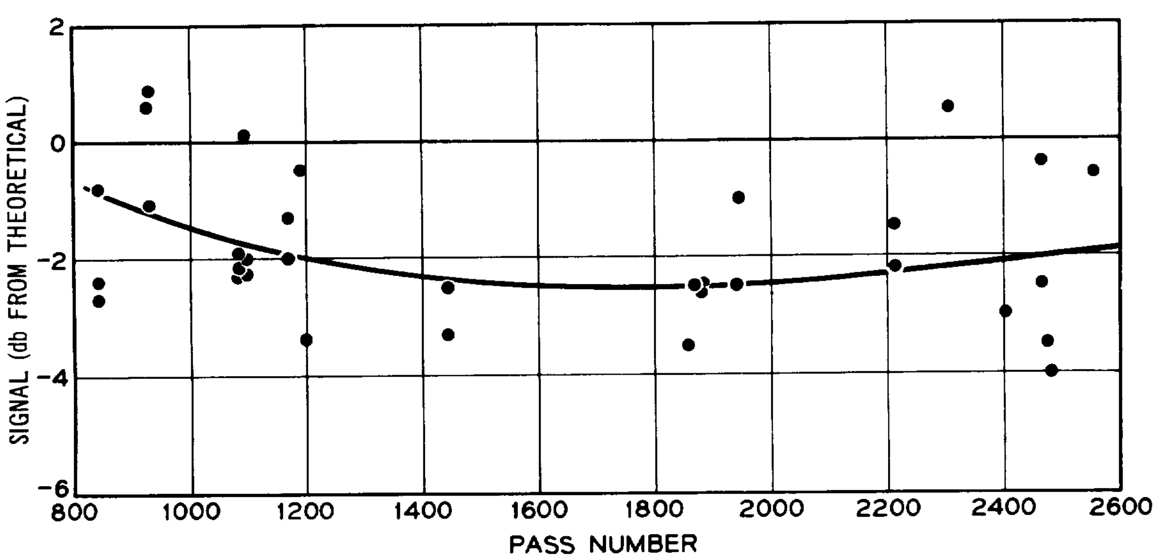

Figure 4 – Received signals compared with theoretical values

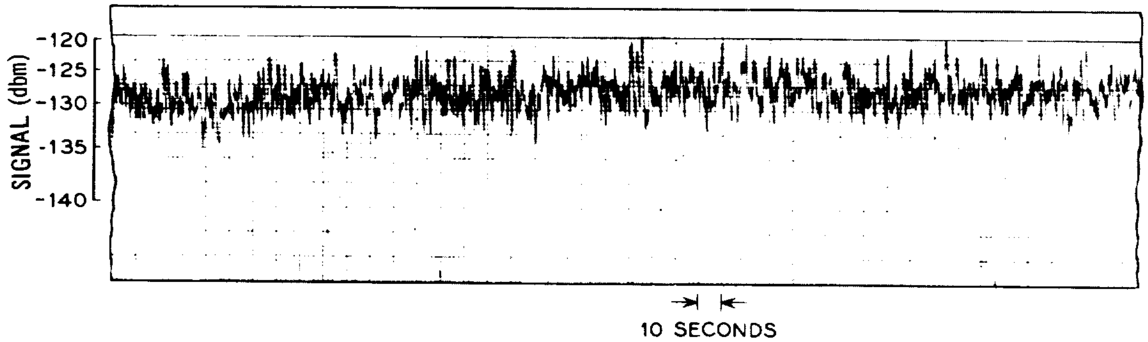

Figure 5 – Return signal from the moon (February 8, 1961)

GENERAL ARRANGEMENT OF RADAR SYSTEM

To provide a separate high-powered transmitter and large transmitting antenna for the radar would be expensive and add considerably to the complexity of the systems. For these reasons the transmitter and the transmitting antenna employed for communications (The 60-foot Kennedy dish) were shared by the radar through frequency division. The 4-Mc bandwidth of the transmitter would have allowed a wide separation between the communications and radar frequencies; however, frequency assignment limited this spacing to 1 Mc, with the radar at the higher frequency. Although this spacing was sufficient to allow separation of the signals in the receivers, a somewhat greater spacing would have been advantageous.

The radar transmitter and receiver are each gated to be on for half of the time and off for half, i.e., the diplexing is accomplished by having the receiver on only when the transmitter is off. The gating rate is varied between 15 and 45 cycles depending upon the balloon's range. To avoid overloading of the radar receiver's early stages by the ungated communications transmitter, a radar receiving site was chosen at a distance of approximately one and one-half miles from the transmitter. The receiving antenna, having a conical scan, is "slaved" to the transmitting antenna by means of synchro signals carried over telephone lines (see Figure 1). There is no lobing of the transmitting antenna. Pointing-error signals are sent over telephone lines back to the antenna-control center, where the appropriate corrections in antenna pointing are made manually.

TRANSMITTER

Since the transmitter is described in detail in Reference 3, it will be discussed only very briefly here. The radar section of the exciter consists of a crystal-controlled oscillator, a gated harmonic generator, and an attenuator (Figure 6). The radar signal is combined with the 70-Mc communications signal in a mixing amplifier. In the mixer and amplifier unit which follows the mixing amplifier the 70-Mc signal is modulated up to 960.05 Mc and the radar signal up to 961.05 Mc. These two signals are amplified simultaneously by the klystron power amplifier having a bandwidth of 4 Mc.

The extremely high sensitivity of the receiver necessitates turning off the transmitter whenever the receiver is on. It was found that intolerable interference at the receiver occurred whenever a 71-Mc oscillator was on at the transmitting site, even though the oscillator was well filtered, shielded, and disconnected from the exciter. This situation resulted from the high gain of the transmitter between the 71-Mc input and the antenna. Therefore it was necessary to employ an oscillator operating at a subharmonic of 71 Mc and to gate the harmonic generator that is required to obtain the desired frequency.

During simultaneous operation the transmitter power is shared, with 7.5 kw normally going to the communications channel and 2.5 kw to the radar. Because of amplitude nonlinearities in the transmitter, there is interaction between the two signals. In the first

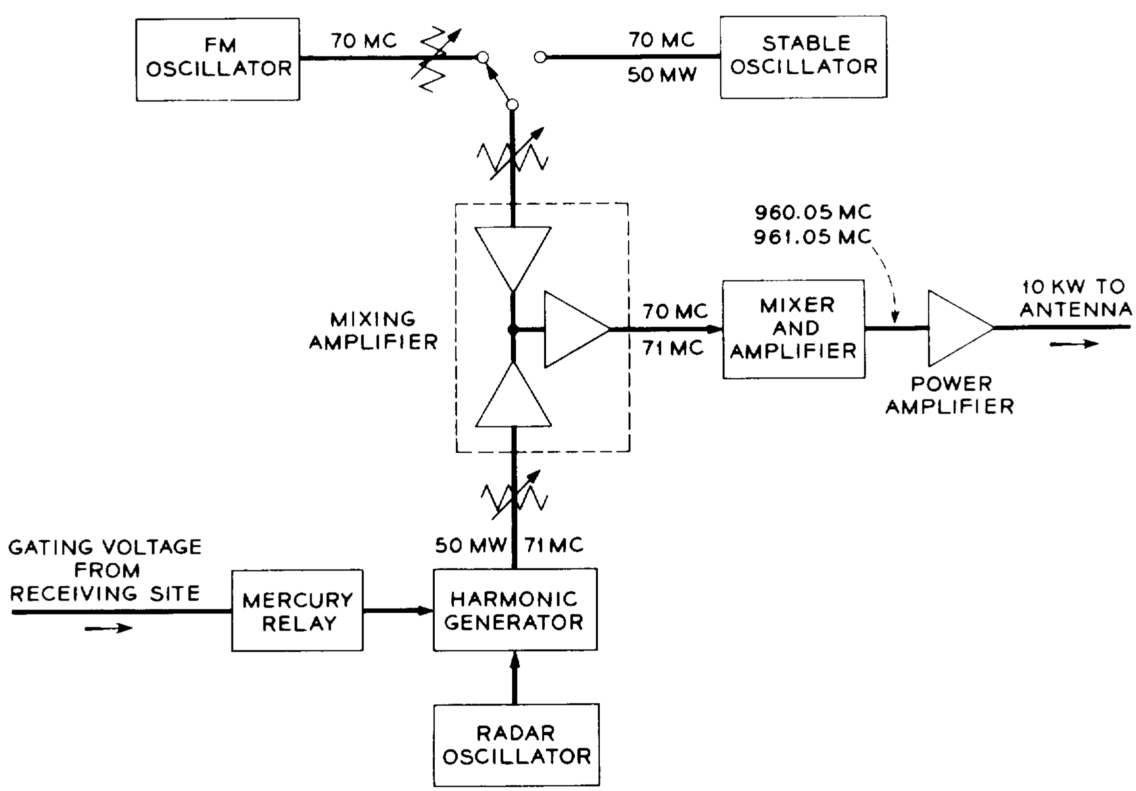

Figure 6 – Block diagram of Echo I transmitter

case, pulsing of the radar signal produces amplitude modulation of the communications signal at the pulse-repetition rate. This crosstalk was reduced to a tolerable value, largely because the pulse-repetition frequency is very low. Secondly, the radar signal is compressed a significant amount by simultaneous presence of the communications signal. For this reason it is necessary to adjust the two signals to the desired values with both present rather than to adjust each individually. This is discussed more fully in Reference 3.

RECEIVING SYSTEM

Figure 7 presents a block diagram of the complete radar receiving system. The 961.05-Mc signal received by the conically scanned antenna is amplified by a low-noise parametric amplifier and heterodyned down to 30 Mc. To avoid the need for rotary joints, this amplifier and a section of the 30-Mc IF amplifier are mounted directly on the antenna and move with it in both azimuth and elevation. The 30-Mc output is conducted to the radar shack through a length of flexible coaxial cable. This IF signal is passed through a crystal filter having a 200 kc, bandwidth which is sufficient to take care of Doppler shift but also narrow enough to remove the interference picked up from

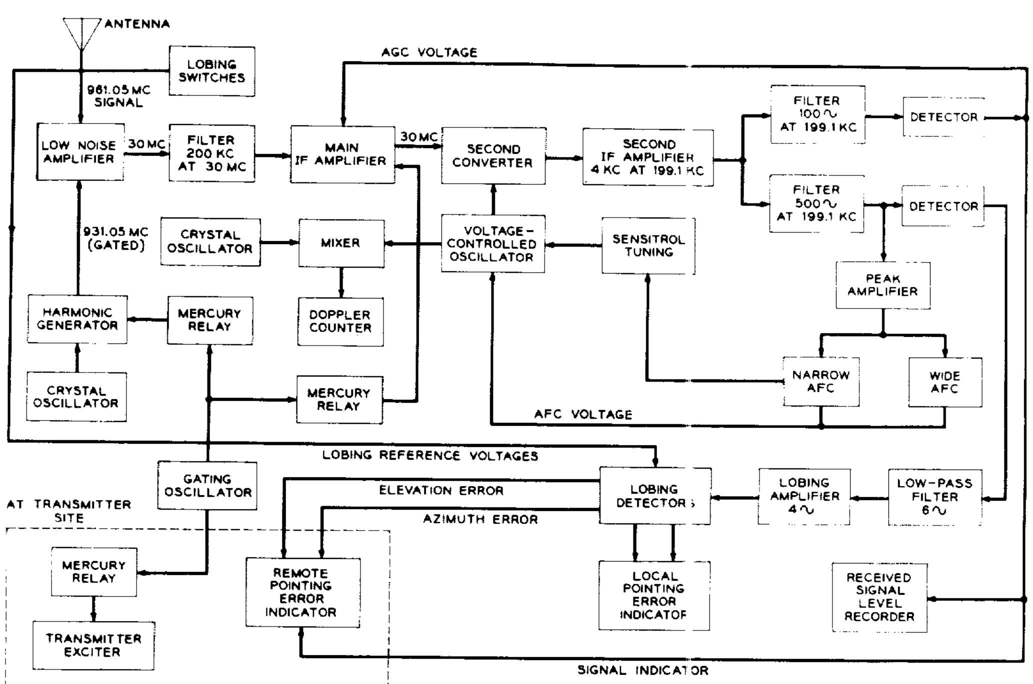

Figure 7 – Radar receiving system

the communications transmitter. After filtering, the 30-Mc signal is amplified by the main IF amplifier, having a bandwidth of about one megacycle.

At the second converter the signal frequency is reduced to 199.1 kc by mixing the 30-Mc with the 29.8009-Mc output of the voltage-controlled local oscillator. The AFC control voltages are applied to this oscillator.

At the output of the 199.1-kc IF amplifier, which has a bandwidth of approximately 4 kc, the signal divides into two paths. One path contains a filter with a 100-cycle bandwidth; the other a filter with a 500-cycle band. The dc output of the detector supplied by the 100-cycle filter is used both to indicate the presence of a signal and as the AGC control voltage for the main 30-Mc amplifier. From another detector, which is energized through the 500-cycle filter, the four-cycle lobing frequency is derived. This lobing frequency is filtered, amplified, and applied to the lobing detectors. At these detectors the lobing voltage is compared with the reference voltages derived from the antenna lobing unit. The resultant signals, which represent errors in azimuth and elevation, are indicated on meters at the receiving site and also on error-indicating devices at the antenna control position.

Because of Doppler shift, the received-signal frequency may differ from that of the transmitted signal by as much as ± 35 kc. Automatic frequency control circuits are provided to keep the receiver in tune. To aid in acquisition, a sample of the voltage-controlled oscillator output is mixed with the output of a crystal-controlled oscillator operating at the nominal beating-oscillator frequency of 29.8009 Mc. The frequency difference between these two oscillators is counted on an electronic counter. To tune in a signal, the voltage-controlled oscillator is adjusted to make the measured difference frequency equal to the expected Doppler shift.

With the satellite at its maximum range of 3000 miles and with the transmitter and receiver each gated to be on for half the time, the optimum gating frequency is about 15 cycles per second. At a minimum range of 1000 miles the optimum pulse-repetition frequency increases to 45 cycles. Gating voltages are provided by an AF oscillator driving mercury relays. To prevent overload, it is desirable to gate the receiver at a point where the signal level is low. The most practical such point appeared to be the circuit of the local oscillator supplying the low-noise amplifier. Gating is done in a harmonic generator supplying this beating-oscillator voltage, and additional gating is applied to the main IF amplifier.

The lobing frequency of four cycles was chosen to be consistent with a 15-cycle pulse-repetition frequency and a one-second integrating time for the lobing-detector outputs.

With the exception of the parametric amplifier and the early stages of the 30-Mc IF amplifier, all the electronic components of the receiver are mounted in a standard relay rack 7 feet high. This bay of equipment is shown on the left-hand side of Figure 8. The cabinet on the right-hand side of the figure contains the antenna-control equipment.

Parametric Amplifier

Although the lobes from the back and sides of the antenna are not small enough in magnitude to warrant use of a maser amplifier, the low noise figure provided by a parametric amplifier is advantageous. Such an amplifier does not require cooling and is, therefore, considerably simpler than a maser. The parametric amplifier was designed and constructed under the direction of H. Seidel of Bell Telephone Laboratories' Murray Hill Laboratory (Reference 4).

The design of this amplifier using a nonlinear capacitance provides for approximately 8 db of gain through frequency up-conversion by means of a nonlinear capacitance.

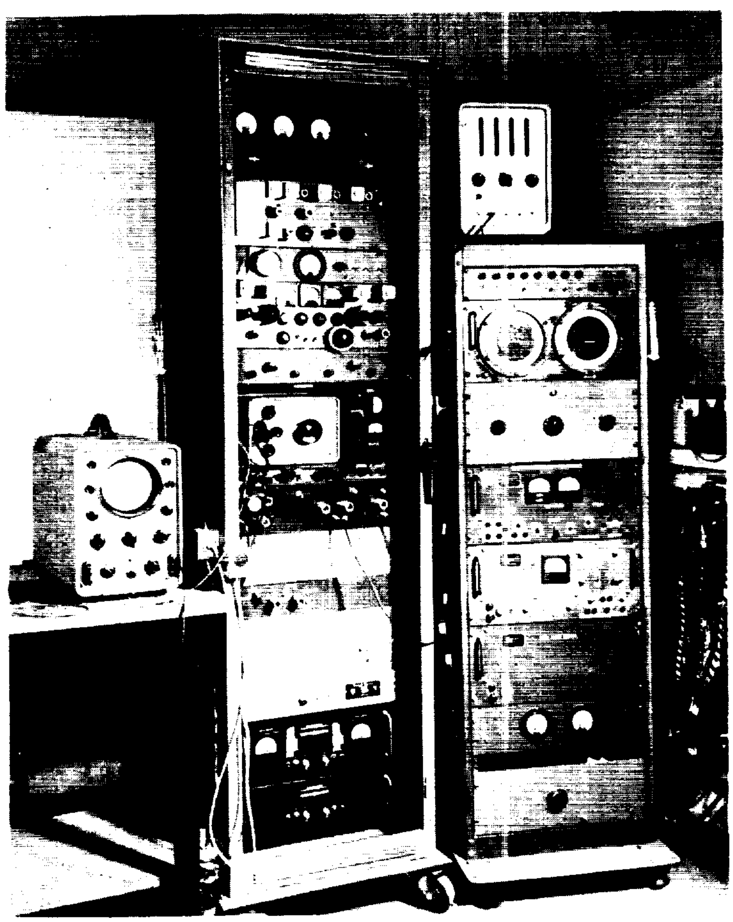

Figure 8 – Antenna receiver and controls

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Additional gain is derived from the negative resistance obtained by pumping such a capacitance (Figure 9). The amplifier is coupled to the antenna by means of a circulator which is enclosed in a heat-insulated container and maintained at 120°F by heating tapes and a thermostat. In this way it is stabilized against variations in ambient temperature. An isolator could have been used in this position if one with sufficient ruggedness and stability had been available.

The pump power is supplied by a Western Electric 445A klystron, operating at a frequency near 11.7 kMc. This frequency is maintained by a mechanical AFC circuit controlled by a Sensitrol* relay which is energized by the signal from a reference cavity. The lower sideband as 10.739 kMc is taken as the output of the amplifier. To obtain the 30 Mc intermediate frequency a beating oscillator frequency of 10.769 kMc is combined with the 10.739 kMc signal in a nonlinear-resistance mixer.

Since the final predetection bandwidth of the receiver is only 100 cycles, it is obvious that the short-term stability of the 30-Mc intermediate frequency must be exceptionally high. This frequency must, therefore, be made independent of the pump frequency, which is only roughly stabilized. The required independence of intermediate frequency is achieved by employing the klystron frequency in the process of heterodyning down as well

*Trade name owned by Weston Instruments Division of Daystrom, Inc., Newark, New Jersey.

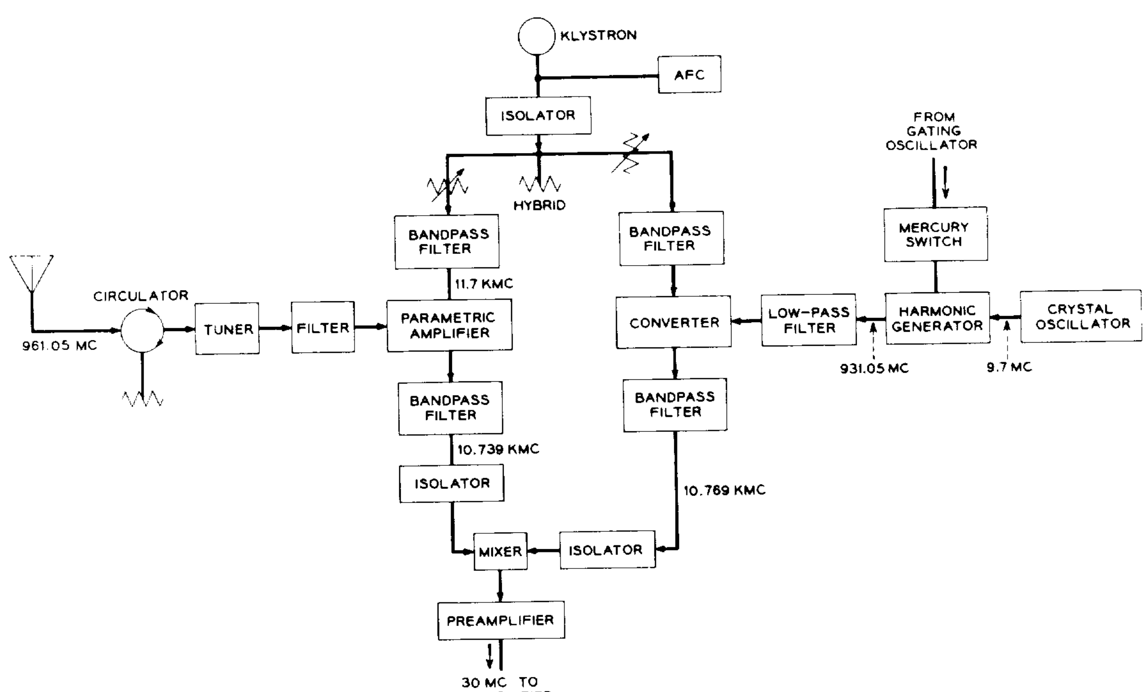

Figure 9 – Radar parametric amplifier

as in heterodyning up. Changes of klystron frequency therefore cancel out in the process of going up in frequency and then back down. The beating-oscillator signal for the down-converter is obtained as follows: The output of a crystal-controlled oscillator operating at approximately 9.7 Mc is multiplied up to 931.05 Mc by means of a harmonic generator. (Gating of the receiver is accomplished by applying a gating voltage to the grid of one of the harmonic generator tubes.) By subtracting the 931.05 Mc from the klystron output, the 10.769 kMc beating-oscillator frequency is obtained.

The bandwidth of the microwave section of the parametric amplifier is 20 Mc. This is reduced to approximately one megacycle by a bandpass filter at the input to the first stage of the 30-Mc IF amplifier. The gain of the microwave section is 22 db; the overall gain 46.5 db. Overall noise figures in the neighborhood of 1.6 db have been measured.

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One db of compression takes place in this amplifier for an input signal of approximately -26 dbm. If the receiving site had been located near the transmitting antenna, interference at the communications frequency would have exceeded this overload value.

Main IF Amplifier

The crystal filter at the input to the main IF amplifier has a total bandwidth of 200 kc. Its characteristic has extremely steep sides, so that the loss at the communications frequency, which falls one megacycle from the center of the band, is probably limited only by leakage around the filter. The amplifier itself has a total bandwidth of approximately one megacycle, and therefore provides some additional discrimination against the interfering communications signal. The design of this amplifier is conventional, and its gain is controlled by the AGC and gating voltages applied to the grids of its tubes.

Voltage-Controlled Oscillator Unit

The voltage-controlled oscillator unit consists of an oscillator and a buffer amplifier. A pair of variable-capacitance diodes shunted across the oscillator tank circuit provides electronic tuning. Two separate circuits supply control bias to the diodes; one for AFC, the other for manual tuning. A one-volt change of bias is sufficient to produce a frequency change of nearly one megacycle, which makes it fairly simple to obtain a very stiff AFC action. This high sensitivity makes it difficult to keep undesired frequency modulation of the oscillator down to acceptable levels. With a receiver bandwidth of only 100 cycles it is desirable to keep this modulation to 10 cycles or less. The modulation which was most difficult to eliminate was that produced by 60-cycle voltages and currents. By operating the heaters of the oscillator and all units near it on dc, and by very careful filtering of all circuits, this modulation was reduced to a tolerable value.

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Second Converter and IF Amplifier

A simplified schematic of this unit is shown in Figure 10. The 30-Mc signal comes in at an impedance of 50 ohms. A tuned transformer steps up this level on the grid of the Western Electric 6AK5 tube used as the converter. The 199.1-kc output of this mixer is amplified through a single tuned stage, then divided into two paths with an untuned single-stage amplifier in each path. One of these amplifiers supplies the input to a three-section tuned filter with a total bandwidth of 500 cycles, whose output is coupled to the AFC unit and the pointing detector through a cathode follower and 50-ohm cables. The crystal filter at the output of the second untuned amplifier has a total bandwidth of 100 cycles and a characteristic with very steep sides. The filtered output drives two detectors in parallel. One of these provides the AGC voltage and is back-biased to produce the desired threshold effect. The AGC voltage is amplified through a one-stage dc amplifier before being applied to the first IF amplifier. A time constant of approximately ten seconds is provided at the amplifier output to prevent the AGC circuit from affecting the four-cycle lobing modulation carried by the incoming signal. A second output from this dc amplifier has a much shorter time constant and goes to a Sanborn recorder on

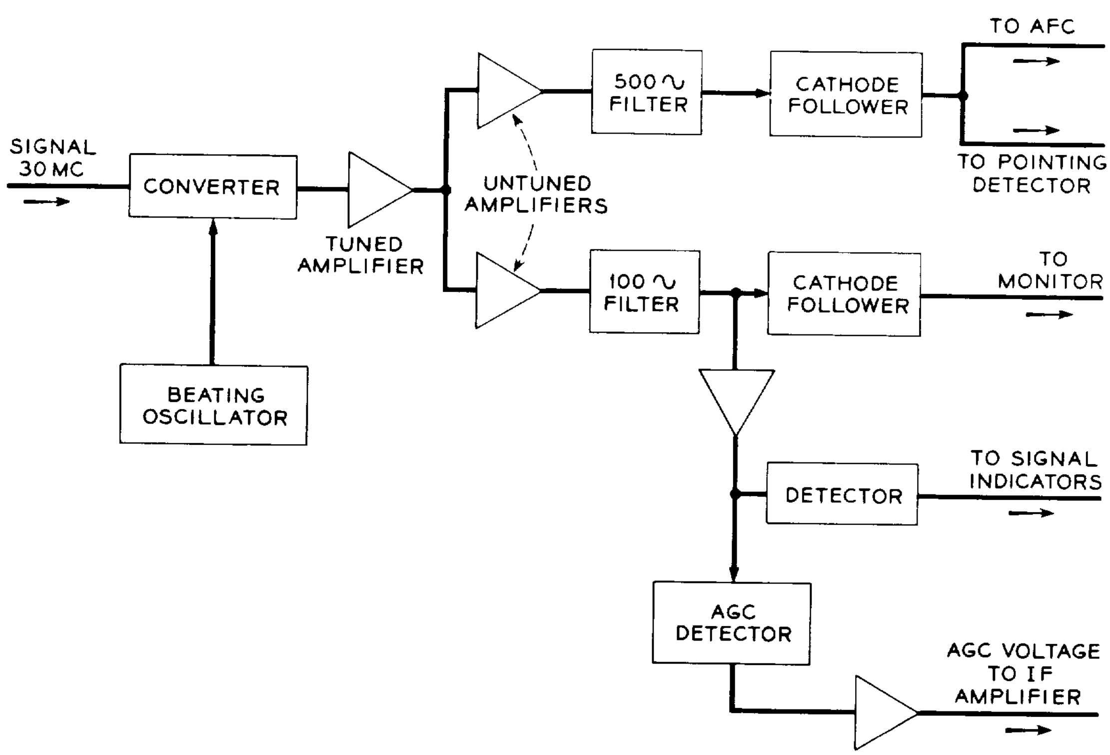

Figure 10 – Radar second converter and second IF amplifier

which a record of the strength of the received signal is provided. The other detector at the output of the narrow filter operates a meter used as a signal indicator.

Lobing Amplifier and Detectors

Before being applied to the lobing amplifier, the output of the detector with the 500-cycle bandwidth is filtered by a low-pass filter with a six-cycle cutoff frequency (see Figure 7). The purpose of this filter is to prevent the pulse-repetition frequency from entering the lobing amplifier. The input to the amplifier is provided with an adjustable phase-shifting network which makes it possible to maintain correct phase with respect to the lobing reference voltages. The lobing amplifier, which is untuned, employs simple RC circuits for coupling the various stages.

Each lobing detector consists of a Western Electric 276D mercury relay operated by one of the lobing reference voltages. These voltages, in quadrature, are derived from a pair of microswitches operated by cams on the antenna scanning unit. The simplicity of the lobing detection system is made evident by Figure 11. It can be seen that the grids of a pair of phase-splitting triode tubes are supplied in parallel with the four-cycle lobing voltage. The plate of one triode is coupled to one input terminal of the elevation relay; the cathode of the triode is connected to the other input terminal of the same relay. The elevation error voltage is taken from the output terminal. If the four-cycle voltage has a component in phase with the reference voltage applied to that particular relay, a charge is built up on the capacitor C_0 across the output terminal; a voltage component in quadrature with the reference voltage causes no change in the average charge on the capacitor. In this way, azimuth and elevation errors are separated. The voltage across C_0 indicates both the sense and magnitude of the pointing error.

The azimuth and elevation error voltages are displayed before operators in the form of meter readings and also as spot positions on a cathode ray oscilloscope. The time constants of these display circuits are adjustable. For satellite tracking a time constant of 3 seconds appears to be about optimum; for moon tracking the optimum time constant increases to about 7.5 seconds.

Automatic Frequency Control

At the 961-Mc operating frequency the Doppler shift at the radar receiver can be as much as ± 35 kc. To keep the signal within the 100-cycle band of the receiver requires a rather "stiff" AFC circuit. To meet the simultaneous requirements on sensitivity and stability a quartz crystal discriminator is employed; its characteristic is shown in Figure 12. With the output of this discriminator connected to the voltage-controlled oscillator, nearly 60 db of negative feedback is obtained and the average frequency of the received signal is held to within a few cycles of the midband of the 100-cycle filter.

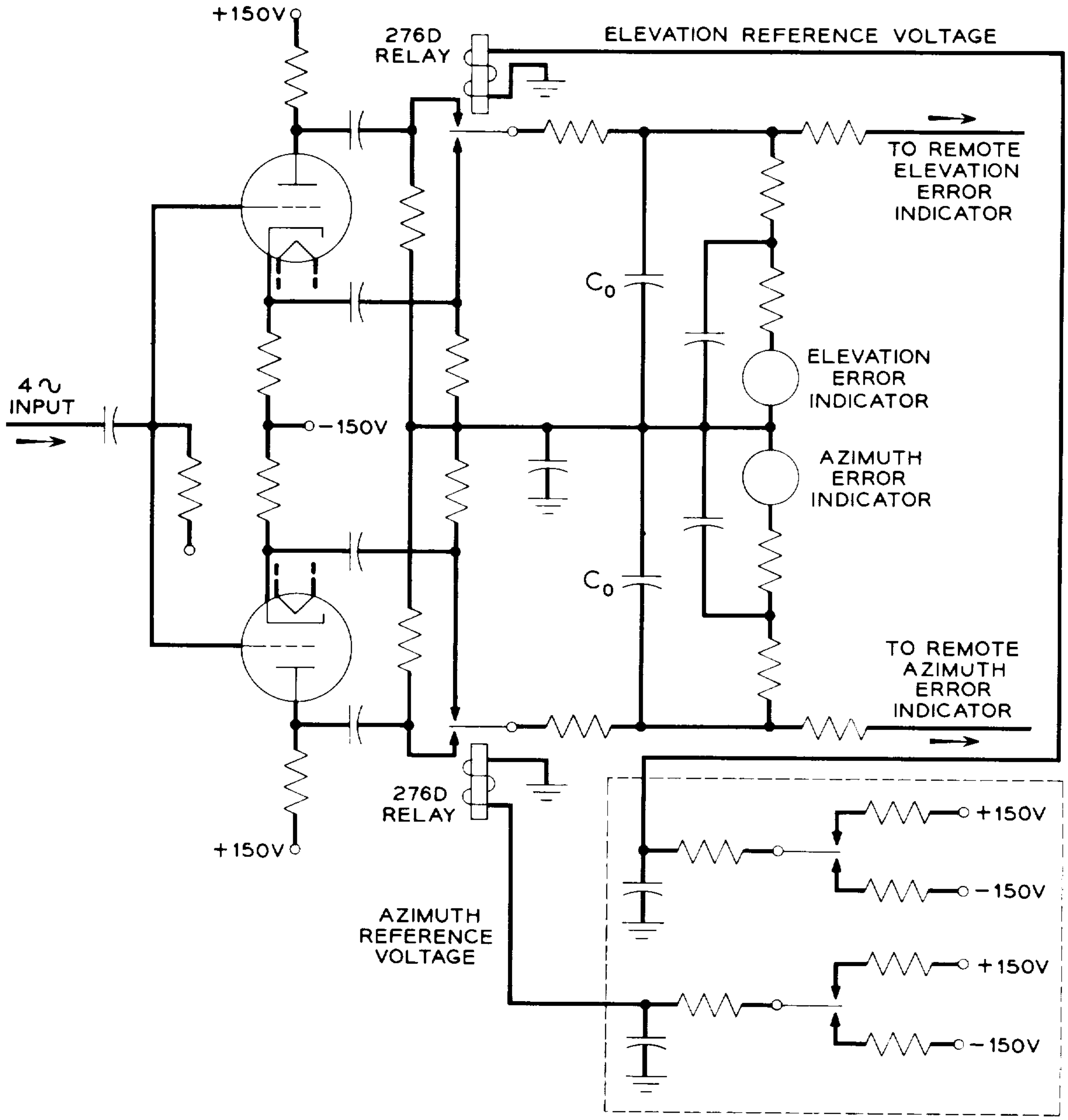

Figure 11 – Radar lobing detectors

To keep pace with the change of Doppler frequency as a pass progresses, a motor-driven tuning control is also provided. The motor is controlled by a Sensitrol relay, which in turn is activated by the output of the crystal discriminator. This mechanical control keeps the receiver approximately tuned at all times and thereby removes much of the burden from the electronic AFC circuit.

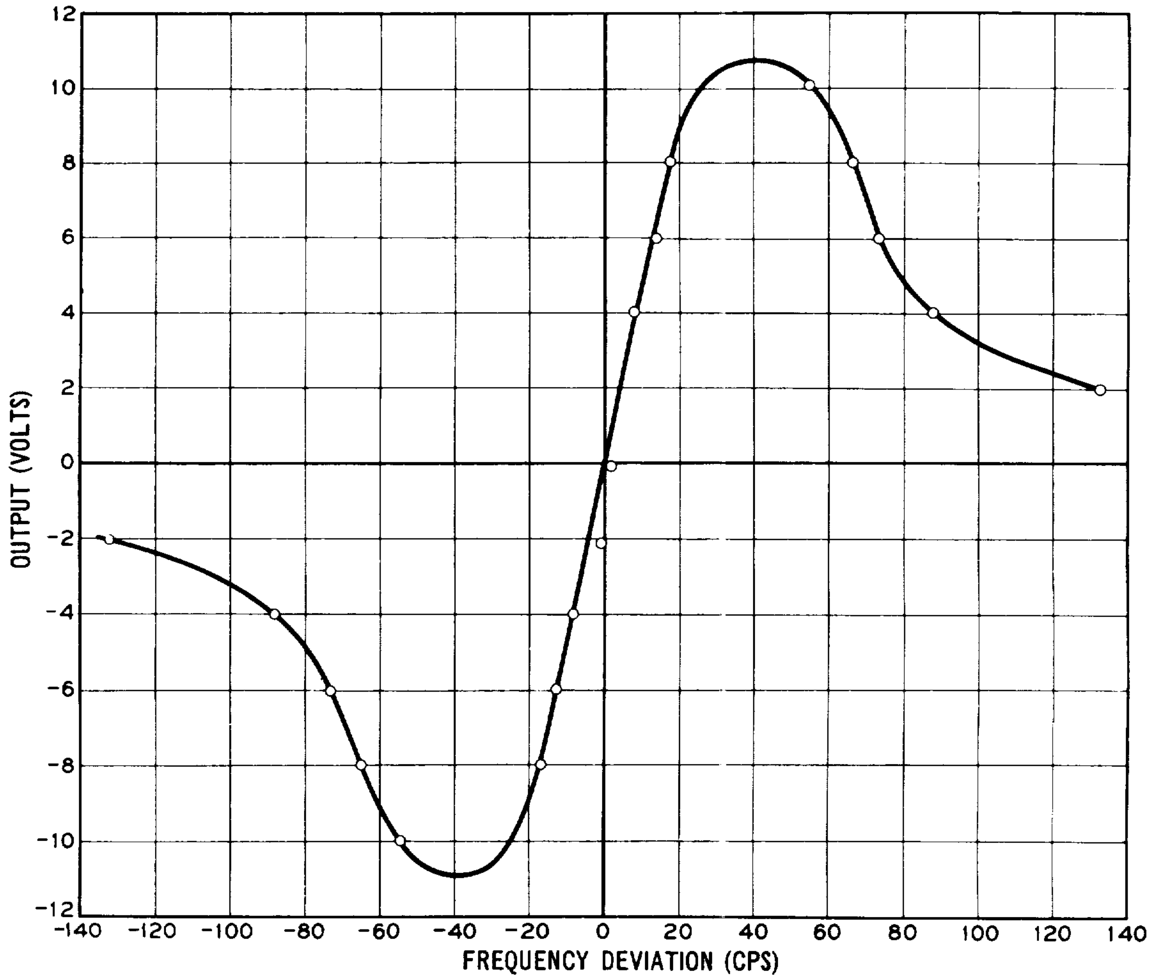

Figure 12 – Frequency characteristic of frequency discriminator

As an aid in acquiring the signal, a wider-band discriminator is also provided. This circuit, which provides 30 db of feedback, brings the signal to within the pull-in range of the crystal discriminator, after which the latter takes control. The pull-in range of the wider circuit is about ± 500 cycles.

When considering the narrow bandwidth of the receiver, the constantly changing Doppler shift, and the short time available for acquisition, it is obvious that there is a tuning problem in acquiring the signal. The difficulties are reduced considerably by the availability of data on the rate-of-change of the balloon's range at all times during the pass. From these data it is possible to calculate the corresponding Doppler shifts. Usually the only data required are those at the start of the pass. In Figure 7, it is seen that one output of the voltage-controlled oscillator is combined in a mixer with the output of the voltage-controlled oscillator. The frequency of the crystal oscillator is equal to the nominal frequency of the voltage-controlled oscillator, i.e., the frequency at which it should be set to bring in a signal with zero Doppler shift. Any difference between the two frequencies applied to the mixer is read on the counter connected to its output.

With the above arrangement the procedure in tuning the receiver is as follows: From orbital data, the Doppler shift at the time in question is calculated. The frequency of the voltage-controlled oscillator is adjusted to cause the counter to indicate a frequency equal to the Doppler shift. If the calculated Doppler were exact and if the various oscillators were perfectly stable, this procedure would result in perfect tuning. To make up for discrepancies, however, a small amount of manual tuning about the calculated frequency is usually required.

Receiver Calibration and Testing

Two reference-signal sources are available at the Crawford's Hill for the purpose of testing and calibrating the receiving system. By employing these sources it is possible to determine the gain and noise power output of the receiver as well as to check pointing accuracy. Checks and calibrations are usually made before each pass.

Antenna

The radar receiving antenna consists of crossed dipoles mounted in front of a reflecting disk to accept circularly polarized waves.* This feed (Figure 13) is mounted at the focus of an 18-foot parabolic reflector by means of a quadrupod consisting of four sections of aluminum tubing. The fiberglass cover which normally protects the feed from the weather was removed for the photograph. The parabolic reflector, fabricated of aluminum tubing and mesh (by Prodelin, Inc.), was chosen because it was lighter than other available reflectors of the same diameter.

Figure 14 shows the complete antenna, mounted on its supporting tower. The small building at the right of the picture houses the receiving equipment.

Since the received signal is circularly polarized it was not feasible to obtain conical scan by simple rotation of the feed. Rather, the feed was caused to rotate about the axis of the antenna in such a way that the radiators always remain parallel to themselves; i.e., the vertical dipole remains truly vertical and the horizontal dipole horizontal. The radiators are mounted at the center of the reflecting disk, and this center point is moved in a circle about the antenna axis without any corresponding rotation of the disk about its own axis. The desired motion is obtained by supporting the disk on three motor-driven cranks.

*The design of this dipole assembly was based on suggestions by personnel of the Jet Propulsion Laboratory of the California Institute of Technology.

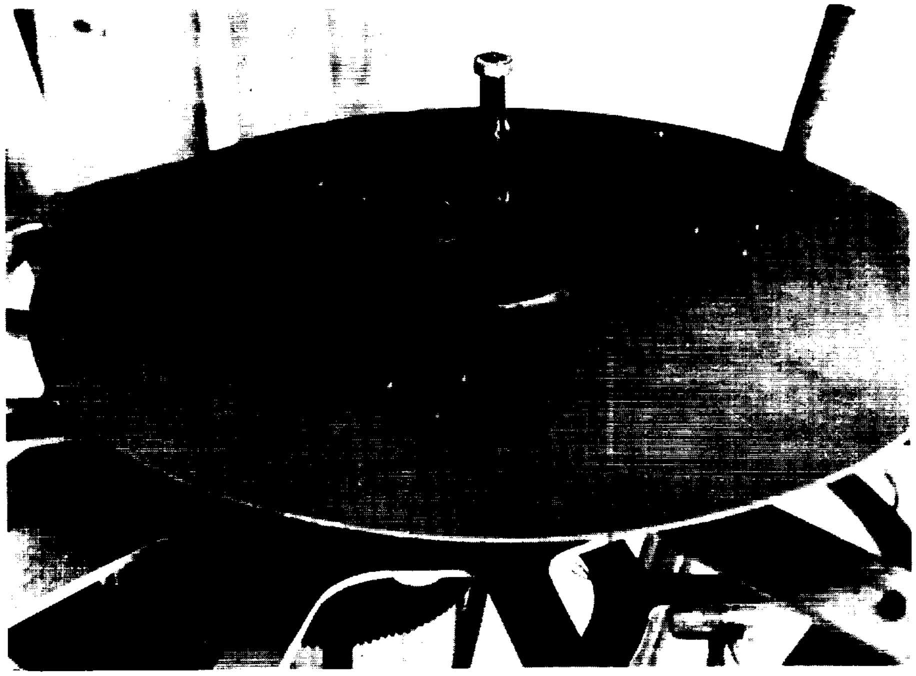

Figure 13 – Antenna feed

Figure 14 – Echo I radar receiving antenna

To minimize losses, the coaxial line from the antenna feed to the low-noise amplifier has a diameter of 1-5/8 inches. This rigid, pressurized line is connected to the rigid line supporting the dipoles by a short length of flexible cable which allows scanning of the feed; no rotary joint is required.

The antenna has a gain of 32.6 db and a beamwidth of 3.9 degrees. Because of the conical-scan feature, the antenna feed is always displaced by two inches from the center-line of the reflector. This results in a beam shift of 1.2 degrees with a resultant loss of approximately 1.5 db of gain along the antenna axis.

In spite of the fact that the parametric amplifier is equipped with a circulator at its input, it was considered important to provide an accurate impedance match between the antenna and its transmission line. By careful adjustment of the various dimensions, a return loss greater than 50 db at the operating frequency was obtained for the dipole assembly alone. This loss remained greater than 20 db over a range of ± 50 Mc. With this feed at the focal point of the mesh reflector and with its fiberglass cover in place, the minimum return loss was still measured at greater than 20 db over the 100-Mc band, although the frequency at which the best match occurs is different than for the dipoles alone (Figure 15).

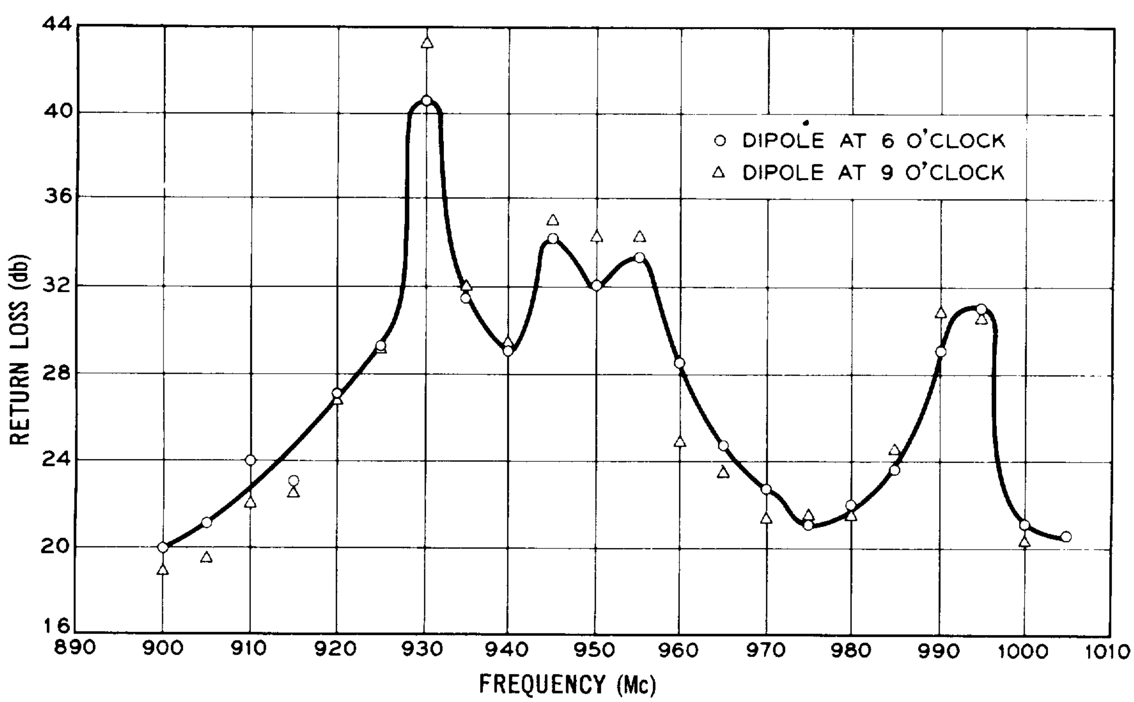

Figure 15 – Antenna match. Feed with reflector

The lobing reference voltage is obtained from two single-pole double-throw switches operated by a pair of cams placed in quadrature to each other and driven by the lobing motor. It was found necessary to shield these switches and to filter the leads going to them in order to avoid interference in the receiver.

ANTENNA MOUNT AND DRIVES

The receiving antenna is supported on, and driven by, a war surplus SCR-584 radar antenna mount, which is supported, in turn, on a steel tower fabricated for the purpose. The center of the reflector is approximately 15 feet above the ground (see Figure 14).

This mount had originally carried an antenna only 6 feet in diameter, and the much greater weight and inertia of the Echo antenna increased the drive problems considerably. As a result of corrosion and wear in the gearing, the antenna drive was found to be very rough—a difficulty which was aggravated by substitution of the larger antenna. Furthermore, the increased inertia upset the characteristics of the feedback loop included in the positioning control system. The greater torque obtained by applying a 10:1 speed reduction to both the azimuth and elevation drive motors smoothed out the drive to a satisfactory degree. In spite of the speed reduction the antenna is still capable of a maximum rate of 4.5 degrees per second in azimuth and 2.4 degrees per second in elevation, which is sufficient for tracking the balloon.

Figure 16 shows a plot of azimuth lag error versus angular rate. Except for the rare orbits that pass directly overhead, the maximum rate is 0.5 degree per second; the corresponding lag error is seen to be 0.04 degree or less.

The SCR 584 antenna mount was originally equipped with only one-speed control transformers. To improve positioning accuracy and to operate with the synchro generators on the transmitting antenna, the system was converted to 1-and-36 speed in both azimuth and elevation. The 1-and-16 speed position-read-out synchros were also converted to 1-and-36 speed in order to be consistent with the rest of the Echo system; these speed changes were accomplished by adding gear trains.

In one experiment it was a simple matter to set up the system to provide auto-tracking of the moon by the receiving antenna only. In this case the transmitting antenna was positioned manually. Because of the low angular rates involved it should not be difficult to obtain completely automatic tracking of the natural satellite. But thus far it has not been considered worth expending the necessary effort to obtain automatic tracking of the balloon.

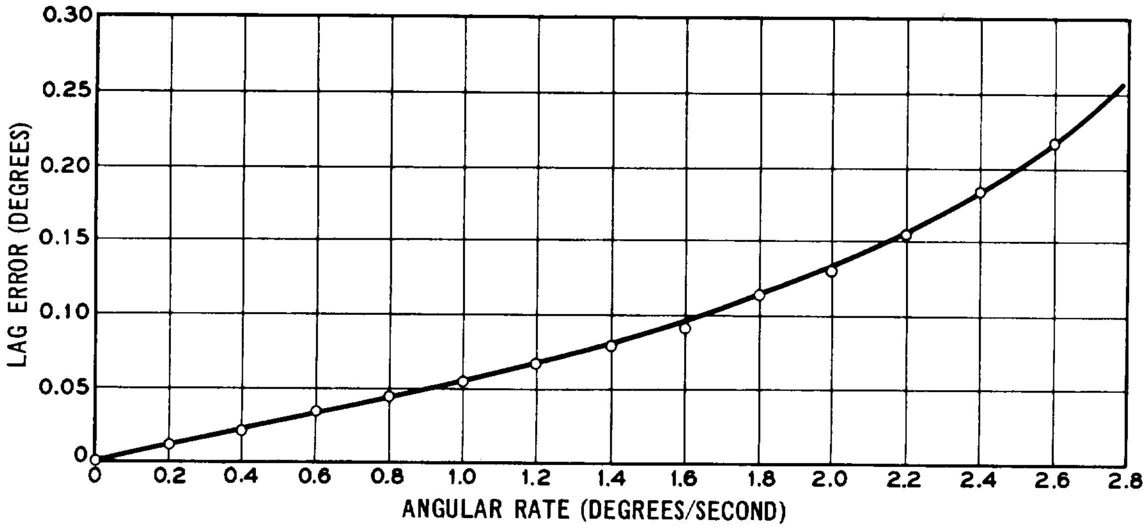

Figure 16 – Azimuth lag error

CONCLUSIONS

Although the performance of the radar as designed is adequate, it could be improved in several ways. Considerable improvement is noted when the transmitter is employed exclusively for radar, not only because of the 6-db increase in power but also because of the absence of extraneous signals which result from some forms of modulation of the communications channel. A further reduction in the amount of residual frequency modulation of the beating oscillator supplying the second converter is also desirable.

Automatic adjustment of the pulse-repetition frequency to the optimum value at all times would also be a worth-while improvement. The present method—making manual adjustments—is satisfactory when the radar is employed solely for antenna pointing. When the system is measuring the path loss to the balloon and back, misadjustments of the pulse-repetition frequency reduce the accuracy of these measurements. Automatic control of the pulse rate should, therefore, provide more accurate results.

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$$P_R = -128 \text{ dbm.}$$

For $R = 3000$ miles and $W = 2.5$ kw,

$$P_R = -147.1 \text{ dbm.}$$

At a temperature of 300°K, the kT noise power is -174 dbm per cycle of bandwidth. For a 100-cycle band and a noise figure of 1.8 db the noise power is

$$W_N = -174 + 20 + 1.8 = -152.2 \text{ dbm.*}$$

At the maximum range of 3000 miles the predetection signal-to-noise ratio in the 100-cycle band is $152.2 - 147.1 = 5.1$ db. For the 500-cycle band the noise power is 7 db greater and the predetection signal-to-noise ratio is -1.9 db.

For a considerable number of the passes tracked, the full 10-kw output of the transmitter was given over to the radar. This 6-db increase in transmitted power brings the calculated signal-to-noise ratio at the maximum range of 3000 miles up to 11.1 db at the output of the 100-cycle filter, and 4.1 db at the output of the 500-cycle filter. At the minimum range of 1000 miles the ratios are 30.2 and 23.2 db respectively.

Postdetection filtering provides a very considerable improvement in the pointing signal-to-noise ratio. For example, a one-second time constant at the output of a phase detector is equivalent to a bandwidth of 0.16 cycle, providing a reduction of 34.9 db in noise power when compared to a 500-cycle bandwidth. This improvement, however, cannot be realized under all conditions.

*This value of noise power is to be expected during measurements of system sensitivity, since the signal-generating equipment has a noise temperature of approximately 300°K. A similar noise level is to be expected when the antenna is at zero elevation as it is at acquisition. In this position there are trees, ground, etc., in the beam. It has been found experimentally that the noise power decreases about 2 db as the antenna beam is elevated from the horizon to the zenith.

Appendix B

Earth-Moon-Earth Path Loss

The following values apply in calculating the earth-moon-earth path loss:

Peak transmitted power	= 10 kw = +70 dbm,
Average transmitted power	= 5 kw = +67 dbm,
Transmitting antenna gain	= 43.1 db,
Receiving antenna gain	= 32.6 db,
Lobing loss	= 1.5 db,
Total line loss	= 0.5 db
Received power	= -128 dbm,
Path loss, L	= 128 + 67 + 43.1 + 32.6 - 1.5 - 0.5
	= 268.7 db.

According to Trexler* the path loss is 258 db at 300 Mc and increases at the rate of 6 db per octave. At 961.05 Mc,

$$\begin{aligned} L &= 258 + 20 \log_{10} (961.05/300) \\ &= 258 + 10.1 \\ &= 268.1 \text{ db.} \end{aligned}$$

*Trexler, J. H., "Lunar Radio Echoes," Proc. I.R.E. 46(1):286-292, January 1958